

Probabilistic assessment of “dangerous” climate change and emissions pathways

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Climate policy decisions driving future greenhouse gas mitigation efforts will strongly influence the success of compliance with Article 2 of the United Nations Framework Convention on Climate Change, the prevention of “dangerous anthropogenic interference (DAI) with the climate system.” However, success will be measured in very different ways by different stakeholders, suggesting a spectrum of possible definitions for DAI. The likelihood of avoiding a given threshold for DAI depends in part on uncertainty in the climate system, notably, the range of uncertainty in climate sensitivity. We combine a set of probabilistic global average temperature metrics for DAI with probability distributions of future climate change produced from a combination of several published climate sensitivity distributions and a range of proposed concentration stabilization profiles differing in both stabilization level and approach trajectory, including overshoot profiles. These analyses present a “likelihood framework” to differentiate future emissions pathways with regard to their potential for preventing DAI. Our analysis of overshoot profiles in comparison with non-overshoot profiles demonstrates that overshoot of a given stabilization target can significantly increase the likelihood of exceeding “dangerous” climate impact thresholds, even though equilibrium warming in our model is identical for non-overshoot concentration stabilization profiles having the same target.

Article 2 | anthropogenic interference | risk management | uncertainty analysis | integrated assessments

Article 2 of the United Nations Framework Convention on Climate Change states its ultimate objective as: “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference (DAI) with the climate system.” This level should be achieved within a timeframe sufficient to allow ecosystems to adapt naturally to climate change, ensure that food production is not threatened, and enable economic development to proceed in a sustainable manner (ref. 1 and www.unfccc.de). Thus, DAI may be characterized in terms of the consequences (or impacts) of climate change (2). Although the evaluation of DAI can be informed by scientific evidence and analysis, it is ultimately a normative decision, influenced by value judgments, sociopolitical processes, and factors such as development, equity, sustainability, uncertainty, and risk. The perception of DAI will likely be different depending on geographical location, socioeconomic standing, and ethical value system. However, plausible uncertainty ranges for DAI thresholds can be quantified from current scientific knowledge (3), which can inform the development of policies to avoid potentially “dangerous” outcomes. More than 180 signatories to the United Nations Framework Convention on Climate Change have committed to prevention of DAI, and we argue that climate-change policy decisions should be conceptualized and policy options compared in terms of preventing or reducing the probability of dangerous climate impacts. Such a risk-management framework is familiar to policymakers and

appropriate for climate policy decisions, which by necessity require decision making under uncertainty (4–6).

Because of the complexity of the climate-change issue and its relevance to international policymaking, careful consideration and presentation of uncertainty is essential when communicating scientific results (7–10). As expressed in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR), the scientific community can provide essential information underpinning decisions on what constitutes DAI (11). For instance, scientific research can provide information on the intensity and spatial scale of climate impacts associated with future climate change. Further, the scientific community can provide specific probabilistic guidance on the implications of different policy choices and their respective likelihood of avoiding dangerous climate impacts. We present a probabilistic framework for differentiating climate policy options by assessing their likelihood of avoiding thresholds for DAI. We apply this framework to a range of emissions pathways resulting in stabilization of atmospheric greenhouse gas concentrations, with and without overshoot of the stabilization concentration. These emissions pathways imply different development scenarios and magnitudes and timing of climate mitigation efforts.

DAI Metrics

Aggregate Metric. In ref. 12, we presented a cumulative density function (CDF) of the threshold for DAI, based on the IPCC reasons for concern about climate change (ref. 3 and Fig. 1). Each category represents a semiindependent “consensus estimate” of a metric for measuring “concern” about the climate system. We view these metrics as indicators of the level of global mean temperature change associated with DAI in the categories presented. Specifically, we view the increasing scale and intensity of impacts represented by the color gradient in each category as an estimate not only of physical climate impacts, but also of societal perceptions of danger from those impacts. Interpreted in this way, increasing temperatures will progressively exceed thresholds in each metric and cumulatively contribute to the likelihood that the climate change occurring will be perceived to be dangerous by humanity as a whole. In other words, as warming intensifies, more and more stakeholders will perceive that DAI thresholds are being exceeded (based on their own value-driven assessments of what constitutes DAI in various metrics), cumulatively adding to the global perception of danger from climate change.

Abbreviations: DAI, dangerous anthropogenic interference; CDF, cumulative density function; CO₂e, CO₂ equivalent; SC, slow change; RC, rapid change; OS, overshoot scenario; IPCC, Intergovernmental Panel on Climate Change; TAR, Third Assessment Report; EU, European Union; PDF, probability density function; MEA, maximum exceedance amplitude; DY, degree years.

See accompanying Profile on page 15725.

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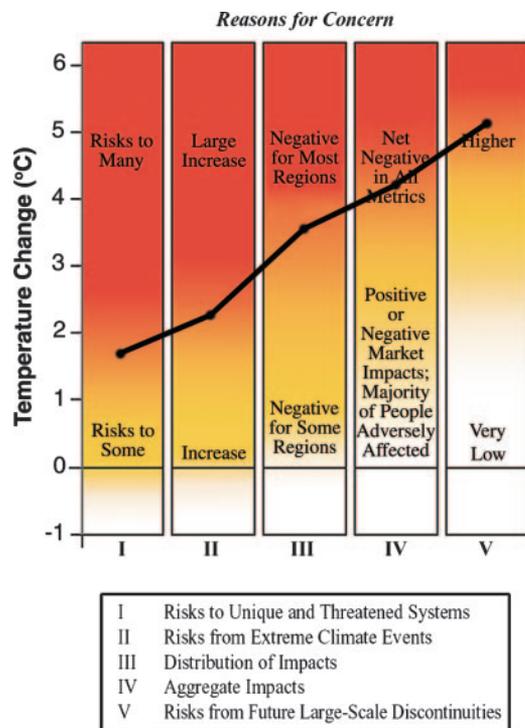


Fig. 1. An adaptation of the IPCC reasons for concern figure from ref. 12, with the thresholds used to generate our CDF for DAI- \emptyset . Five reasons for concern are conceptualized, mapped against global temperature increase. As temperature increases, colors become redder, indicating increasingly widespread and/or more severe negative impacts. We use the transition-to-red thresholds for each reason for concern to construct a CDF for DAI- \emptyset .

In ref. 12, we represented this accumulation of danger by assigning data points at the threshold temperature above which each metric becomes red (solid black line in Fig. 1), and assuming that crossing each threshold cumulatively adds an equal probability (20%) of reaching a global “aggregate” DAI threshold (see ref. 12 for a more complete description of methods). This aggregation method acts to average the thresholds of each impact metric, producing a median, 50th percentile threshold of 2.85°C above current temperatures, and a 90% confidence interval of [1.45°C, 4.65°C] (12). Here, we label this CDF DAI- \emptyset , because it is an average of impacts accumulating across all five metrics in Fig. 1. We presented a “traceable account” (13) of our assumptions in producing this aggregation, and we believe a similar account should be made each time such a definition is created by any analyst, as others, such as Wigley (14), have done.

Aggregation Methods. This aggregation method used to produce DAI- \emptyset is not intended to represent our (or other analysts’) preferred assessment of DAI, although it might represent some stakeholder assessments. Rather, it represents the simplest first-order summation of impact metrics. To clarify the thinking behind our use of this method, a brief discussion follows. Maintaining a traceable account of any aggregation first requires disaggregation into individual “stakeholder metrics,” followed by transparent reaggregation, explicitly choosing weights on each metric to represent different assessments of impacts and value positions associated with these assessments. As we discussed in ref. 12, there are many ways that DAI could be interpreted from Fig. 1, or from other sources (e.g. ref. 15, which suggests measuring vulnerabilities in terms of the “five numeraires”: market losses, human “excess

deaths,” species extinctions, increasing inequity, or loss of quality of life). Some stakeholders may value impacts in one category above all others or may factor information from several impact categories into their evaluations of DAI. An individual who, to some extent, values multiple impact categories, but who is not convinced that crossing the lowest threshold under consideration will constitute dangerous change in his estimation, may choose weights for each individual threshold and derive an averaged threshold somewhere between the individual thresholds in a manner similar to DAI- \emptyset . Another individual who recognizes multiple climate impacts may respond to the existence of multiple, additive risks from climate impacts by increasing her risk aversion and choosing a lower threshold for DAI than that suggested by even the impact category with the lowest threshold. However, we use the DAI- \emptyset metric in this work not to represent an individual evaluation of DAI, but as a demonstration that at some stage there must be, implicitly or explicitly, an aggregation of stakeholder values in any internationally negotiated climate policy target based on preventing DAI. The history of the international climate negotiations (e.g., Alliance of Small Island States-proposed targets vs. negotiated Kyoto targets) has shown that some policymakers are willing to delay action until “enough” impacts have accumulated or set as a target a level of climate change that may cross thresholds for DAI for some particularly vulnerable populations.⁵ Under these circumstances, we believe the averaging method we present is an appropriate aggregation method to demonstrate our probabilistic framework.

As discussed previously, the stakeholder assessments of DAI that underlie such a global aggregation can vary widely. We present below, as a framework for methods to analyze DAI, an initial step in disaggregating our DAI- \emptyset metric by interpreting each reasons for concern category as representing a limited number of stakeholder prime interests and to show how that could lead to very different DAI thresholds.

Stakeholder Metrics. To represent possible stakeholder DAI metrics and the diversity of possible evaluations of DAI, we produce two CDFs (DAI-I and DAI-V) based on individual reasons for concern categories (columns I and V in Fig. 1), which reflect possible policy perspectives presented by generalized stakeholders in the international climate debate. An Alliance of Small Island States member or a conservation biologist seeking to preserve biodiversity (or others sympathetic to these values) may focus their evaluation of DAI on Fig. 1, column I risks to unique and threatened systems, which represent temperature change associated with risks to unique human settlements such as low-lying small island nations or vulnerable coastal states like Bangladesh and to unique or vulnerable ecosystems, like mountaintop communities or Arctic indigenous cultures dependent on sea ice. A midlatitude nation, or a nation with high adaptive capacity and little concern for impacts elsewhere in the world, might ignore considerable impacts to other regions of the world and be most concerned with abrupt nonlinear global climate changes, basing its evaluation of DAI on Fig. 1, column V, risks from future large-scale discontinuities such as ocean circulation alterations or deglaciation of Greenland. We construct these stakeholder CDFs based on the increasing climate risk in each of these categories indicated by the reasons for concern color scale. We define our DAI-I and DAI-V CDFs by constructing normal distributions with median equal to the transition from yellow to orange in each category (orange signifying a medium level of impacts), and two-SD (2σ) length equal to the distance from this

⁵During the negotiations leading to the creation of the Kyoto Protocol, the Alliance of Small Island States submitted a draft protocol requiring 20% cuts in emissions by 2005 for industrialized nations. Clearly, the Kyoto targets are not as stringent as this target proposed by one stakeholder group.

transition to the beginning of the color scale (the transition from white to yellow). This analysis yields a median threshold for DAI-I of 1.2°C above current temperatures with a 90% confidence interval of [0.3°C, 2.1°C] and a median threshold for DAI-V of 4.15°C with a 90% confidence interval of [3°C, 5.3°C].[¶] As with all our metric definitions, there are other equally plausible methods by which to construct such distributions. Our purpose, as mentioned earlier, is to demonstrate a quantitative framework for analysis and policy debate, not to offer our model-dependent numerical results as “answers” or recommendations.

Finally, an important geopolitical stakeholder in the climate policy debate is the European Union (EU). With the withdrawal of the United States from the Kyoto Protocol, the EU now ranks as the largest current and historical emitter of greenhouse gases involved in negotiating binding international mitigation policies. The European Council, in keeping with a precautionary approach and perhaps influenced by the recognition of multiple, additive climate risks as discussed above, has adopted a long-term policy goal of limiting global average temperature increase to 2°C above preindustrial temperatures. In a growing number of studies, this threshold is also designated as a temperature limit above which dangerous climate impacts may occur (17, 18). Clearly, a policy target such as this one cannot capture the probabilistic nature of any assessment of future climate impact thresholds, nor is it intended to do so. Temperature increases <2°C may still induce dangerous changes, and increases >2°C may not, all subject to the variety of definitions and metrics of danger discussed above. The EU threshold has both political and analytical history, so we adopt the EU policy goal as a third stakeholder threshold, DAI-EU.

Emissions Pathways and DAI

Stabilization Profiles. The United Nations Framework Convention on Climate Change (1) has called for parties to consider “stabilization of greenhouse gas concentrations,” and much recent international debate has centered on the desirable level of atmospheric greenhouse gas concentrations at which to stabilize, or the level in keeping with avoiding DAI. Many research efforts have produced concentration stabilization profiles to drive models investigating the climate implications of various emissions pathways.^{||} O’Neill and Oppenheimer (20), for example, produce stabilization profiles that reach a range of CO₂ equivalent (CO₂e) stabilization levels through three approach categories: slow change (SC), rapid change (RC), and overshoot scenario (OS). These profiles differ from many stabilization profiles in that they consider emissions of aerosols and all significant radiatively active gases beyond CO₂ and a wider range of approach pathways to final stabilization levels. Although these profiles are only a subset of plausible profiles, they are representative of the middle of the range of published profiles, yet are different enough to allow us to clearly demonstrate the probabilistic frameworks we are offering in this analysis, especially for overshoot profiles that many analysts have suggested will be the

[¶]Research published after the TAR has indicated that some abrupt nonlinear global changes, such as breakdown of the Greenland or Western Antarctic ice sheets, may be triggered by lower temperature thresholds than those currently indicated in Fig. 1, column V (e.g., ref. 16). Therefore, a stakeholder basing his evaluation of DAI on Fig. 1, column V would likely produce a distribution for DAI thresholds lower than the one reported here if this information were taken into account, as it is likely to be in the next IPCC assessment in 2007.

^{||}In this article, we make an effort, as in ref. 19, to differentiate between emissions scenarios, which represent descriptions of possible future states of the world and the characteristics relevant for emissions, emissions pathways, which represent time-evolving paths for global emissions of greenhouse gases and aerosols, and concentration profiles, which represent time-evolving trajectories for atmospheric concentrations of greenhouse gases and aerosols.

most likely future path for greenhouse gas concentrations over the next centuries.

Risk Assessment. The temperature profile associated with an emissions pathway depends on uncertainty in our understanding and modeling of the climate system. Thus, any stabilization level for greenhouse gases can produce a distribution of possible temperature increases, some of which may exceed a given threshold for DAI, some of which may not. Analysis of stabilization profiles and their likelihood of success in achieving the goal of avoiding DAI requires explicit treatment of the uncertainty in the climate system. Our approach is quantitative: probabilistic analyses of temperature distributions associated with each profile. To quantify this probabilistic framework, we apply our DAI metrics to representative concentration stabilization profiles generated by emissions pathways from the three approach categories in ref. 20, for 500- and 600-ppm CO₂e stabilization levels. All profiles reach their target stabilization level by the year 2200, with the OS profiles peaking in 2100 at a level 100 ppm CO₂e above the final target. These stabilization profiles, well within the published range, are primarily offered to demonstrate the framework, not to bound future outcomes, as higher and lower emissions pathways are still quite plausible.

Temperature Projections

Climate Sensitivity Uncertainty. Much of the uncertainty in current understanding of the climate system is captured by the so-called climate sensitivity, defined as the equilibrium global mean surface temperature increase from a doubling of atmospheric CO₂. Using general circulation models, the IPCC has long estimated the climate sensitivity to lie somewhere between 1.5°C and 4.5°C (21), without indicating the relative probability of values within, let alone outside, this range. Recent studies produce distributions wider than the IPCC range, with significant probability of climate sensitivity >4.5°C (e.g., refs. 22–24). The likelihood of avoiding any given temperature threshold for DAI is extremely sensitive to the uncertainty associated with climate sensitivity, as demonstrated by us (12) and Hare and Meinshausen (25). Specifically, this likelihood is very dependent on the upper bound of the climate sensitivity distribution, as larger climate sensitivities will contribute most significantly to the likelihood of DAI threshold exceedence.

For any stabilization profile, differences in climate sensitivity will lead to very different projected temperature profiles. The IPCC TAR presents future global average temperature profiles by forcing a simple climate model tuned to several complex atmosphere-ocean general circulation models, driven by the six illustrative scenarios in ref. 21. Each “tuning” uses a different climate sensitivity, resulting in the temperature ranges presented in the TAR for each illustrative scenario. O’Neill and Oppenheimer (20) also use a simple climate model of the type used in the TAR to produce temperature profiles based on their stabilization profiles and choose three climate sensitivities within the IPCC range to produce a sensitivity analysis. Neither analysis, nor other recent research (26), relates emissions pathways, which implicitly or explicitly require climate mitigation policy decisions, to probability functions for avoiding DAI.** This linkage, which we also make in this article, has become a focus in recent literature (19, 25, 27).

In our analysis, we use three probability density functions (PDFs) from two published sources, the PDF from Andronova

**O’Neill and Oppenheimer (20) compare the future temperature profiles generated by their emissions pathways to thresholds for individual climate impacts that may be considered dangerous, and consider the sensitivity of their results to three values for climate sensitivity, but they do not produce PDFs for their results.

and Schlesinger (22), including solar forcing, and the expert and uniform prior distributions from Forest *et al.* (23). Use of these PDFs allows us to sample a range of uncertainty in climate sensitivity representative of the range reported in current publications.

Climate Modeling. To generate consistent temperature time series for application of our DAI metrics, and to explore the probabilistic range for future temperature change implied by uncertainty in climate sensitivity, we use the radiative forcing time series for the SC, RC, and OS profiles for 500- and 600-ppm CO₂e stabilization levels to force a simple two-box climate model. This model was originally developed by Schneider and Thompson (28) and modified by Nordhaus (29) for use in the dynamic integrated climate and economy model. We modify the Nordhaus version to reduce the time step from 10 years to 1.^{††}

Owing to the many model-dependent assumptions inherent in the use of such highly simplified models, we emphasize that our quantitative results using this simple model are not intended to be taken literally, but we do suggest that the probabilistic framework and methods be taken seriously: they produce relative trends and general conclusions that better represent a risk-management approach than estimates made without probabilistic representation of outcomes. The demonstrated application of threshold metrics for DAI to emissions pathways extends the risk-management framework presented in ref. 12, introducing a method for assessing the probability of DAI for future climate profiles produced by other climate models and stakeholder metrics.

Probabilistic Temperature Time Series. We generate temperature time series by running this simple climate model with a range of climate sensitivities sampled from our climate sensitivity distributions. For a given emissions pathway, running the model under each different climate sensitivity will produce a different temperature time series. Thus, by sampling many times from each climate sensitivity distribution, running the model with each value for climate sensitivity, and recording the temperatures produced, we generate PDFs for future temperature change, for each emissions pathway in any given year, based on the uncertainty in climate sensitivity. All temperatures are expressed as temperature increase above the year 2000.

In this article, we present distributions based on an aggregation of the separate results by using each of the three climate sensitivity distributions listed above, despite recognizing that, when using distributions produced with different methodologies, it is better methodological practice to present results separately, as we did in ref. 12. As our primary purpose here, however, is to demonstrate a framework for probabilistic analysis, and because the choice of any of these three climate sensitivity distributions does not change the qualitative properties of our analysis, we choose to present aggregate results for the sake of clarity of framework.^{‡‡} Given that there is no assessment of the differential confidence assigned to each

published distribution nor a basis for choosing one distribution as most likely, we choose to aggregate over these three distributions, presenting results approximating the range of uncertainty among published climate sensitivity distributions.

We also generate PDFs for the equilibrium temperature predicted by each combination of climate sensitivity and radiative forcing stabilization level. The equilibrium temperature increase (which will lag the radiative forcing by many decades owing to the thermal inertia of the climate system) for a given combination of climate sensitivity and radiative forcing can be calculated as

$$\Delta T_{EQ} = (\Delta F / \Delta F_{2x}) \times \Delta T_{2x}, \quad [1]$$

where ΔT_{EQ} is the equilibrium temperature increase above preindustrial levels, ΔF is the radiative forcing in W/m² for a particular stabilization level, ΔF_{2x} is the radiative forcing estimate for a doubling of atmospheric CO₂, and ΔT_{2x} is the climate sensitivity. For these calculations, we set $\Delta F_{2x} = 3.71$ W/m², as suggested in ref. 30.

DAI Analysis

Probabilistic DAI Analysis. We map our aggregate metric (DAI- \emptyset) and stakeholders metrics (DAI-I, DAI-V, and DAI-EU) for DAI onto PDFs for transient global average temperature increase at 2100 and 2200 for each emissions pathway's concentration profile, and for each equilibrium temperature increase and radiative forcing stabilization level (500 ppm CO₂e, 600 ppm CO₂e). This analysis allows us to characterize and compare emissions pathways in terms of their likelihood of exceedence of DAI thresholds. Fig. 2 compares results for two emissions pathways in 2100 (*a*), in 2200 (*b*), and at equilibrium (*c*), a SC profile stabilizing at 500 ppm CO₂e, and an SC profile stabilizing at 600 ppm CO₂e, both of which approach their stabilization level more slowly than the other (RC, OS) profile types. Fig. 2 displays the relationship for each profile between the temperature increase above 2000 levels chosen as the median threshold for DAI in each metric and the probability of exceedence of that threshold. The lower the threshold for DAI, of course, the higher will be the probability of exceedence. These curves are calculated for each concentration profile from the PDFs for temperature increase in a given year described above. These PDFs can be used to construct CDFs by integrating the PDFs. Any point on one of the curves in Fig. 2 is equal to one minus the corresponding point on a CDF constructed from the PDF for temperature increase above 2000 at the indicated time (2100, 2200, in equilibrium). In other words, any point on a CDF for a temperature increase at a given time indicates the probability (between zero and one) that the temperature increase at that time is equal to or below that level. If a threshold for DAI were set at that level, this probability would represent the probability of compliance with that threshold. One minus the probability of compliance represents the probability of exceedence (see the examples below). Fig. 2*a* and *b* indicates transient temperature increase, whereas temperatures approach the equilibrium distributions displayed in Fig. 2*c*, provided atmospheric concentrations are stabilized indefinitely.

To evaluate the probability of exceedence for our metrics for DAI, we indicate, in Fig. 2, the median DAI threshold of our aggregate DAI metric (DAI- \emptyset), the median thresholds of our DAI-I and DAI-V metrics, and the DAI-EU threshold.^{§§} For example, the SC500 emissions pathway we use has a probability of exceedence of the DAI-EU threshold of 21% in 2100, 45% in

^{††}The two-box model is of the form:

$$T(t) = T(t-1) + \sigma_1[F(t) - \lambda T(t-1) - \sigma_2[T(t-1) - T_{LO}(t-1)]]$$

$$T_{LO}(t) = T_{LO}(t-1) + \sigma_3[T(t-1) - T_{LO}(t-1)],$$

where $T(t)$ is the temperature in the upper box in year t , $T_{LO}(t)$ is the temperature in the lower box in year t , $F(t)$ is the radiative forcing above preindustrial levels in year t , and λ , σ_1 , σ_2 , and σ_3 are constants as defined in ref. 29. We adjust σ_1 and σ_3 to use a 1-year time step by dividing σ_1 and σ_3 by 10.

^{‡‡}Our presentation of results is intended to demonstrate our probabilistic framework, and presenting separately the results using each climate sensitivity distribution requires, for each analysis step, either one very busy figure or three separate figures displaying essentially the same information. We believe such complexity would obscure the demonstration of our analysis methods while adding little intellectual value.

^{§§}The DAI-EU threshold is defined as 2°C above preindustrial temperatures, while we present temperature distributions of temperature increase above 2000. Therefore, we express the DAI-EU threshold as 1.4°C, based on the central estimate of 0.6°C warming over the 20th century in the IPCC TAR (21).

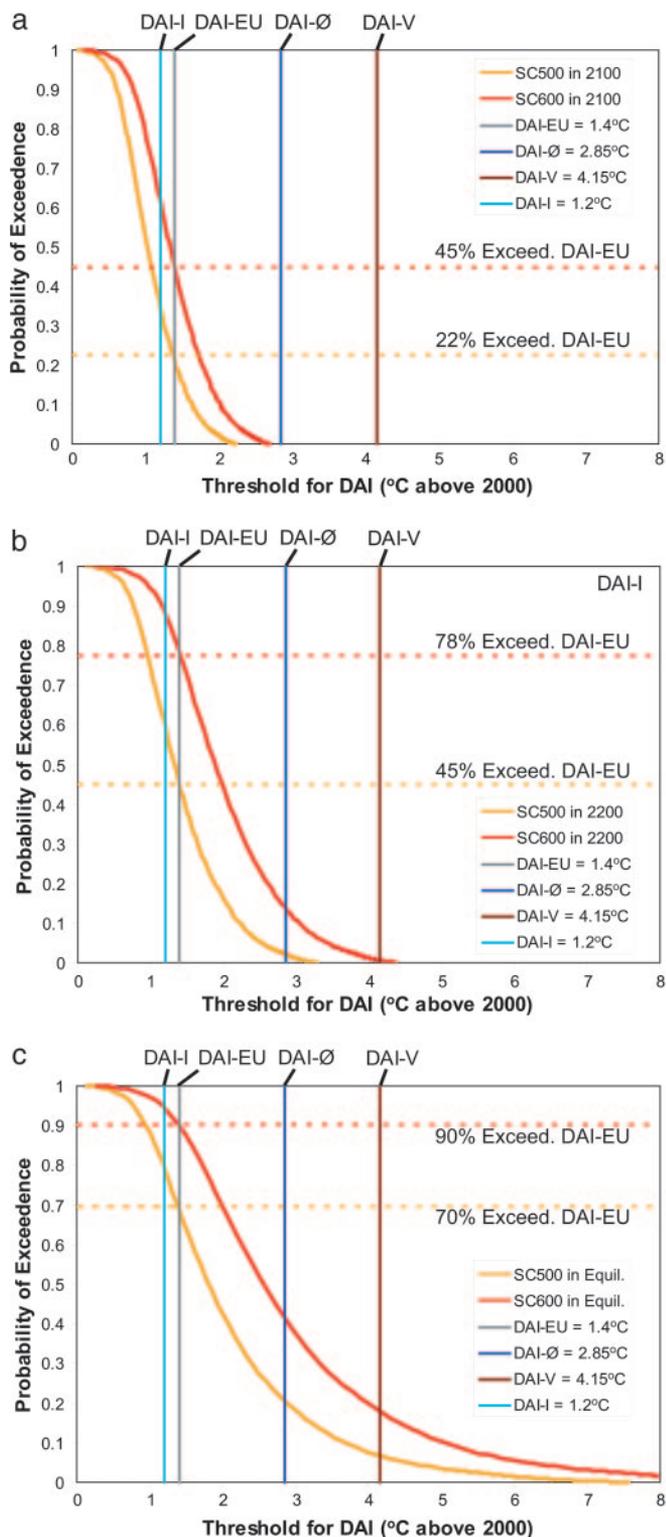


Fig. 2. Comparison of the probability of exceedence of the indicated thresholds for DAI for two concentration profiles, one stabilizing at 500 ppm CO₂e (SC500) and one stabilizing at 600 ppm CO₂e (SC600). (a and b) Probabilities of exceedence for transient temperature increase above 2000 in 2100 (a) and 2200 (b). (c) Probabilities of exceedence in equilibrium. The curves are generated from PDFs for future temperature increase generated by running the simple climate model described in *Climate Modeling* for each concentration profile, sampling from the PDFs for climate sensitivity used in this article. As reported in the text, probabilities of exceedence of the DAI-EU threshold are indicated.

2200, and 70% in equilibrium, under the assumption set used in this analysis, whereas the SC600 pathway we use has exceedence probabilities of 45%, 78%, and 90%, respectively.

As mentioned previously, the quantitative results from our simple model should not be viewed as high-confidence indicators of future outcomes. The specific probabilities of exceedence of DAI thresholds presented in Fig. 2 highly depend on the model formulation (see below) and PDF for climate sensitivity we use. However, the qualitative features of the trends we present are likely to reflect similar features that could be obtained by using more complex models, and we present these results to demonstrate the probabilistic characterization of emissions pathways as a framework we believe can be informative to policy makers when evaluating climate policy options. In addition to the profiles presented in Fig. 2 (SC500, SC600), we examine similar results for stabilization profiles from the other approach categories for stabilization presented in ref. 20 (RC500, RC600, OS500, OS600) and will highlight three properties of these results, beyond reinforcing the well established finding that stabilization at a higher level of atmospheric greenhouse gas concentration increases the probability of exceeding most thresholds for DAI.

(i) The pathway to stabilization has significant impact on the probability of exceeding thresholds for DAI.

This similarly unsurprising result is still quite relevant to ongoing international and domestic national climate policy-making. Comparing trajectories that stabilize at the same level (e.g., SC500, RC500, and OS500) indicates that faster accumulation of greenhouse gases makes exceedence more likely to occur and to occur earlier (see Fig. 3). Additionally, overshoot of the stabilization level leads to significantly greater likelihood of exceedence. We explore these characteristics in more detail in the next section.

(ii) Stabilization at 500 ppm CO₂e can still impose a significant probability of DAI for some stakeholders (e.g., those adhering to DAI-I), whereas stabilization at a level as high as 600 ppm CO₂e may produce a relatively low probability of exceeding some DAI thresholds (e.g., those focusing on DAI-V) before 2200.

With the exception of the SC500 pathway (37%), all six pathways imply a more than 1 in 2 chance by the year 2100 that temperature increases will induce impacts perceived to be dangerous under the DAI-I median threshold (1.2°C above 2000 temperatures). However, under the median threshold for the DAI-V metric (4.15°C), none of the pathways imply a more than 1 in 20 chance through the year 2200. This contrast reinforces the point made earlier and in ref. 12 that what is perceived as dangerous is a value judgment, represented in this analysis by thresholds based on two reasons for concern (see *Stakeholder Metrics*).

(iii) Equilibrium temperature increases far exceed transient temperature changes of the next two centuries.

For all pathways (see Fig. 2), equilibrium temperature increases (and probabilities of exceedence of DAI thresholds) are greater than those seen through 2200. How much greater depends on the ocean model formulation used (see below), which has a major influence on the transient approach to equilibrium temperature increase. Our results suggest that even a stabilization level of 500 ppm CO₂e can imply significant probabilities of DAI threshold exceedence for at least some stakeholders in the long term. How policy makers might value very long-term risks is a function of their concern for sustainability and their method of discounting.

Irreversibility and Path Dependence. The complex response of the climate system to external forcings may include abrupt non-linear climate changes and other impacts essentially irreversible on time scales relevant to policymaking. Paleoclimatic

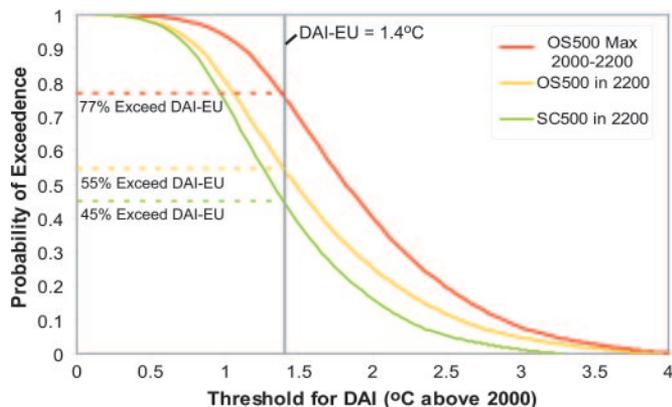


Fig. 3. Comparison of the probability of exceedence of the DAI-EU threshold for overshoot (OS500) and nonovershoot (SC500) concentration profiles stabilizing at 500 ppm CO₂e. The green and yellow curves display probabilities of exceedence for transient temperature increase above 2000 in 2200, and the red curve displays probabilities of exceedence for the maximum temperature reached sometime between 2000 and 2200 for the overshoot (OS500) concentration profile. Although there is only a modest increase in the probability of exceedence of the DAI-EU threshold in 2200 under the two profiles, there is a significant increase in the probability of at least a temporary exceedence of the DAI-EU threshold before 2200.

data and scientific understanding of current components of the climate system indicate that such changes are possible in the future because of anthropogenic forcings. We examine stabilization profiles that differ in their transition to the final stabilization level. Although overshoot profiles may reduce the mitigation costs of reaching a given stabilization level (31–33), they may also increase the climate impacts associated with a given stabilization goal (20, 34). Further, the additional transient warming induced by overshoot stabilization profiles may exceed temperature thresholds for irreversible, abrupt non-linear climate changes or impacts (like species extinctions), which will persist long after the temporary threshold exceedence. The higher and more rapid rise of temperatures will increase the probability of DAI exceedence for overshoot profiles, compared with monotonically increasing profiles reaching the same stabilization level.

As an illustration, Fig. 3 displays curves similar to Fig. 2 for the OS500 profile in 2200 and the maximum temperature increase reached by using that profile between 2000 and 2200. For comparison, the relationship between probability of exceedence and threshold for DAI under the SC500 profile in 2200 (identical to that in Fig. 2b) is also displayed. The concentration overshoot increases the probability of exceeding any given threshold for DAI relative to nonovershoot profiles with the same stabilization level. As stated previously, the SC500 profile has a 45% chance of exceeding the DAI-EU threshold (vertical line in Fig. 3) in 2200. The OS500 profile has a 55% chance of exceedence in 2200 and a 77% chance of exceedence for the maximum temperature increase. In this case, maximum temperatures under the OS500 profile are reached before 2200. Although the OS500 profile only modestly increases the probability of exceedence of the DAI-EU threshold in 2200 compared with the SC500 profile (55% to 45%), the overshoot significantly increases the probability (77%) of temporary overshoot of the threshold before 2200.

We present two metrics for further evaluating the increase in risk of DAI associated with an overshoot profile, pictured in Fig. 4 for an illustrative profile. First, we define the maximum exceedence amplitude (MEA) above a given DAI threshold as the maximum difference between the DAI threshold and a calculated temperature profile through a given time

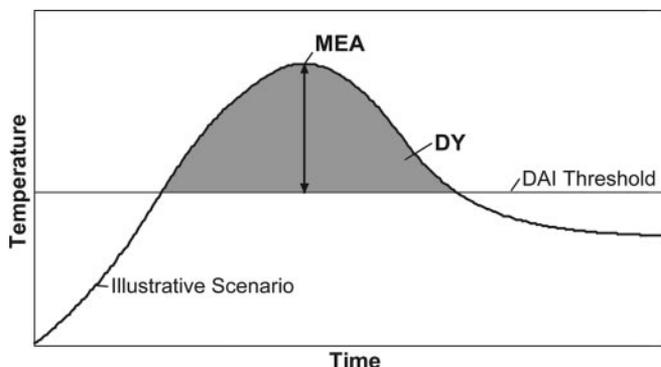


Fig. 4. Visual representation of the MEA and DY metrics. We introduce these tools to differentiate emissions pathways by the degree to which they exceed thresholds for DAI. For the illustrative temperature profile displayed here, MEA is measured as the maximum temperature increase reached above the indicated threshold for DAI (horizontal gray line), and DY is measured as the cumulative exceedence of that threshold by the profile (gray shading).

period. If a temperature profile never exceeds the DAI threshold, the MEA will be negative, representing the closest approach to the threshold during that period. Fig. 5 shows box and whisker diagrams for MEA-EU (MEA for the DAI-EU threshold), for 2000–2250, for the three profiles stabilizing at 500 ppm CO₂e (SC500, RC500, OS500), and the equilibrium temperature distribution for stabilization at 500 ppm CO₂e. In Fig. 5, each box and whisker indicates the 95% confidence interval (horizontal line), 90% confidence interval (vertical lines), 50% confidence interval (box), and median value (dot) and represents the distribution of MEA-EU values from calculations by using our aggregate climate sensitivity distribution (see *Probabilistic Temperature Time Series*). The non-overshoot profiles both have a 50% chance of exceeding the DAI-EU threshold by the year 2250. The overshoot profile has a >75% chance of at least temporary exceedence within that timeframe, with a median MEA-EU comparable with that in equilibrium.

The MEA metric provides information about the maximum

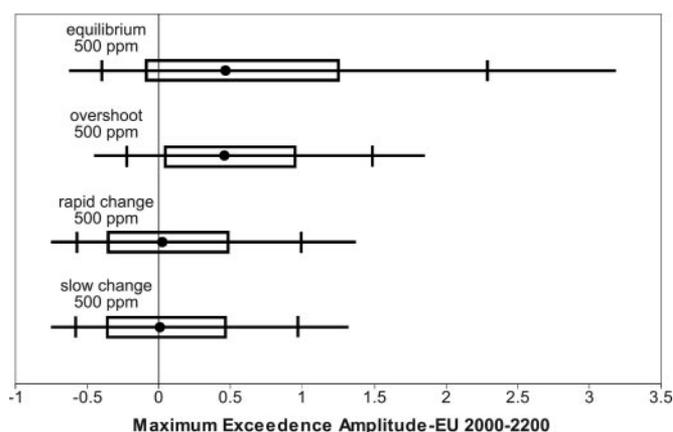


Fig. 5. Box-and-whisker diagrams for the MEA above the DAI-EU threshold, MEA-EU. The diagrams indicate the 95% confidence interval (full horizontal line), 90% confidence interval (vertical tick marks), 50% confidence interval (box), and median value (dot). The lower three diagrams display the distribution of MEA-EU between 2000 and 2200 for the three concentration profiles stabilizing at 500 ppm CO₂e. For comparison, the top box-and-whisker diagram displays the MEA-EU distribution in equilibrium for stabilization of 500 ppm CO₂e. The overshoot concentration profile increases the median and overall range for MEA-EU, compared with the nonovershoot profiles.

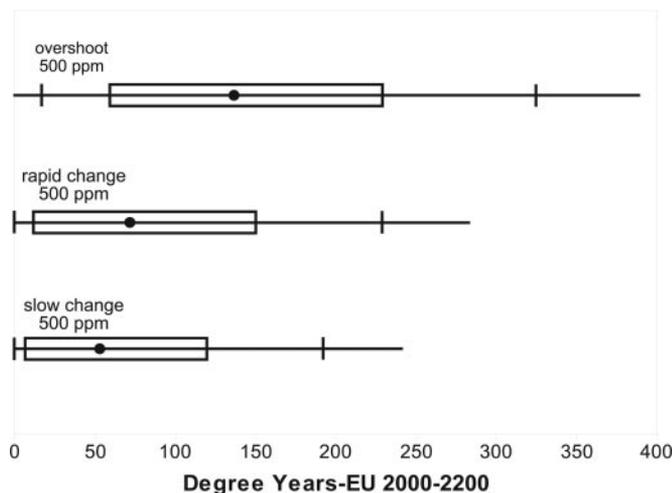


Fig. 6. Box-and-whisker diagrams for DY above the DAI-EU threshold, DY-EU. The diagrams indicate the 95% confidence interval (full horizontal line), 90% confidence interval (vertical tick marks), 50% confidence interval (box), and median value. The diagrams display the distribution of DY-EU between 2000 and 2200 for the three concentration profiles stabilizing at 500 ppm CO₂e. The overshoot concentration profile increases both the median and variance of the DY-EU distribution, compared with the non-overshoot profiles.

temperature reached in a given timeframe and the magnitude of exceedence of a given threshold for DAI. It does not provide information about the duration of exceedence. A prolonged period of temperatures above a threshold for DAI is likely to induce more severe impacts than a short exceedence of equal magnitude. Degree days are a commonly used metric to measure cumulative departure from a given temperature level. For example, heating and cooling degree days are used to measure energy demand, and growing degree days are used in agriculture and pest control. We adopt a similar metric, degree years (DY), as a measure of both the length and magnitude of exceedence of a given threshold for DAI. We define DY for a given time period n , temperature profile T , and threshold DAI , as:

$$DY = \sum_{t=1}^n \begin{cases} T(t) - DAI, & T(t) > DAI \\ 0, & T(t) < DAI, \end{cases} \quad [2]$$

where $T(t)$ is the temperature increase above 2000 in a given year, and only positive values contribute to the sum. DY are the sum of the magnitudes of threshold exceedence in each year of a given time period, in other words, the area under the temperature profile curve but above the DAI threshold for that period (gray shading in Fig. 4). Fig. 6 shows box and whisker diagrams for DY-EU (DY for the DAI-EU threshold), for the period 2000–2200, calculated for the three profiles stabilizing at 500 ppm CO₂e, as in Fig. 5. Each box and whisker again represents the distribution of DY-EU values from calculations using our aggregate climate sensitivity distribution and indicates the same confidence intervals. In parallel with Fig. 5, the overshoot profile greatly increases the DY accumulated above the DAI-EU threshold compared with both nonovershoot profiles, with the median DY value nearly tripling between the SC profile (SC500) and the overshoot profile (OS500).

Together, the MEA and DY metrics characterize in two measures the implications of a climate change profile with respect to a given threshold for DAI. MEA cannot identify the length of exceedence of a threshold, and DY cannot distinguish between a short but large exceedence and a long but low-

magnitude exceedence. The metrics provide complementary information.

Model Uncertainty. The temperature distributions and threshold exceedence probabilities in this article are highly sensitive to the choice of climate sensitivity distribution and ocean model formulation. As stated previously, refs. 12 and 25 both address the sensitivity of transient and equilibrium temperature distributions to the choice of climate sensitivity distribution. The ocean model formulation (e.g., box-diffusion vs. box-advection-diffusion) will not affect the equilibrium temperature distribution, but it can significantly affect the evolution of the transient approach to equilibrium.¹¹ That is, models with deep oceans and slower response times will cross thresholds for DAI more slowly than models with faster response times. We have not explicitly quantified the uncertainty created by this additional uncertain component, but we qualitatively explore some of the implications of ocean model formulation in ref. 36.

Conclusions

Identification of the severity, spatial extent, and salience of impacts determines the level that can be labeled as DAI with the climate system. Determining this level is ultimately a value-laden process, one that will undoubtedly lead to different levels for different stakeholders, in different regions of the world, applying different perceptions and values to the question. Despite the layered complexity of determining DAI, we believe the probabilistic risk management framework we present here and in ref. 12 is an effective method for informing the policy process and evaluating the implications of alternative policy choices with respect to DAI. In this article, we demonstrate a probabilistic framework for evaluating and comparing emissions pathways with respect to their potential for compliance with thresholds for DAI, applying three possible probabilistic metrics for DAI, and the DAI-EU threshold, to several stabilization profiles. An evaluation of the effectiveness of a given emissions pathway or set of policy choices in meeting a policy goal, such as avoiding exceedence of the EU threshold of 2°C above preindustrial temperatures, must explicitly consider the uncertainties inherent in the linkage between atmospheric greenhouse gas concentrations and temperature increase.

For our probabilistic metrics, we provide results at different levels of aggregation. The DAI-Ø metric represents a global aggregation of one interpretation of the thresholds for DAI presented in the IPCC reasons for concern, a simple representation of an aggregation of differentiated stakeholder values. Such aggregation is inherent in any international climate policy negotiation. Our stakeholder metrics, DAI-I and DAI-V, represent assessments of DAI at a more disaggregated level. Such assessments are also likely to be an inherent component of international climate policy negotiations. Further disaggregation ultimately leads to small-scale definitions of vulnerability or danger for certain locations, impact sectors, or populations. We propose that the probabilistic framework we demonstrate here can be applied at any level along this continuum. The most difficult part of any such assessment will be to represent quantitatively the stakeholder metrics of various groups and regions, and then to perform an analysis that, via a traceable account of alternative aggregation weighting schemes, helps to guide decision makers at all scales to determine within this risk-management framework how

¹¹This is strictly true when using a simple climate model with a single equilibrium warming level for a given radiative forcing. Some nonlinear processes not included in our simple model can create multiple equilibria and path dependence (e.g., ref. 35). In such models, OS could imply lower thresholds for DAI than those we report here with this linear model.

much risk of exceedence of DAI thresholds they are willing to accept.

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